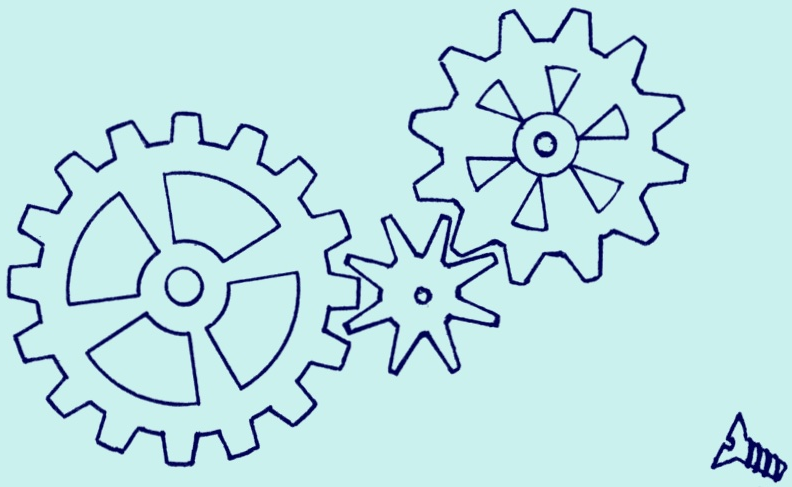
THINGS of science



SIMPLE MACHINES

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SIMPLE MACHINES

Since the very early days of history, man has been devising means to make mechanical work easier. Today we have huge machines to take the place of manual labor, such as the giant shovels that can move thousands of tons of rock a day and gigantic cranes to do the lifting for us.

A machine is defined technically as a device to do work. It may multiply a force, increase the speed of a force, or change the direction of a force.

This unit deals with what are known as simple machines. A simple machine resists a force at one point by supplying a force at another point. A crowbar, a type of lever, is a typical example of a simple machine.

There are several types of simple machines, the inclined plane, wedge, lever, screw, pulley and gear. All machines, no matter how complicated or how large, are based on a combination of one or more types of simple machines.

A machine will produce only as much work as is put into it. Due to friction loss, the amount of work produced by a machine can never be exactly equal to the amount of work applied.

The amount of force put out by a machine divided by the amount of force

put into a machine is called the mechanical advantage, MA, and is expressed as follows:

$$MA = \frac{\text{output of force}}{\text{input of force}}$$

This equation does not take into account the friction involved in the machine and is the ideal mechanical advantage.

In the experiments and problems in this unit, the examples will all show the ideal mechanical advantage rather than the actual mechanical advantage.

First identify your specimens.

PULLEYS—Four pulleys 3/16-inch thick and in diameter sizes of 1/2, 3/4, 1 and 1 1/4 inches.

PULLEY—With large hole, 1 1/16 inch thick by 1 3/8 inch diameter.

SQUARE STICKS—Two wooden sticks 3/8 by 3/8 by 5 inches long.

DOWEL—Round length of wood, 1/4 by 3 inches long.

CORRUGATED PAPER—Two feet long and 3/4 inch wide.

CARDBOARD CUT-OUTS—Two circular cut-outs, 3 and 2 3/8 inches in diameter.

STRING—Two yards.

WIRE—Two 5 1/2-inch pieces.

THUMBTACKS—Four.

SCREW EYES—Four.

LEVER

The lever is the oldest form of simple machine. It is generally described as a rigid bar or rod that rests on a point known as the fulcrum about which it can rotate. It is used in countless ways in our daily living, in balances for weighing, in machines to move heavy boulders, and in some countries even today, as rods placed across the shoulders to carry vegetables and meats to the market, or to transport water from a well.

There are many other examples of levers with which you are all familiar. The nut-cracker, forceps, scissors, crowbar, shovel and broom, all are forms of the lever, as are the foot, arm and jaw in our body mechanism.

Levers can be used in three different ways and are designated, first class, second class and third class levers.

Experiment 1. First class lever. In the lever of the first class, the fulcrum is be-

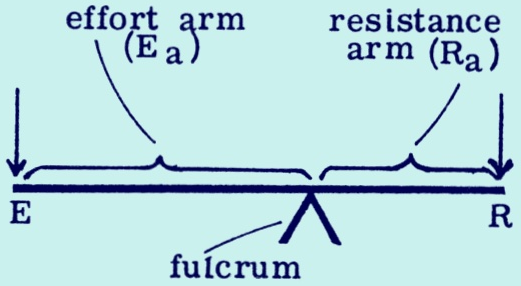

Fig. 1

tween the arm on which the force is exerted, or the effort arm, and the arm on which the resistance is applied, or the resistance arm (Fig. 1).

The lever system was useful to ancient man in removing heavy boulders that stood in his way. A strong stick inserted underneath the boulder with a smaller stone to serve as a prop or fulcrum made the work of moving the boulder much easier. A relatively smaller force on the free end of the lever was required to raise the boulder. The crowbar uses the same principle.

When effort E is applied to the end of the stick, a force is exerted against the resistance R of the rock.

The distance from the end of the stick where effort, E, is applied to the fulcrum is the effort arm, E_a, of the lever and the distance from the fulcrum to the end of the lever under the rock where resistance, R, is exerted, is the resistance arm, R_a.

The mechanical advantage of the lever can be calculated by dividing the length of the effort arm by the length of the resistance arm, or the ratio of E_a to R_a.

In the example above, if E_a is 10 times R_a, the force R applied at the bottom end of the stick to the rock is 10 times as

great as the force E applied at the upper end of the stick. Thus, one-tenth of the effort is necessary to move a heavy boulder (Fig. 2).

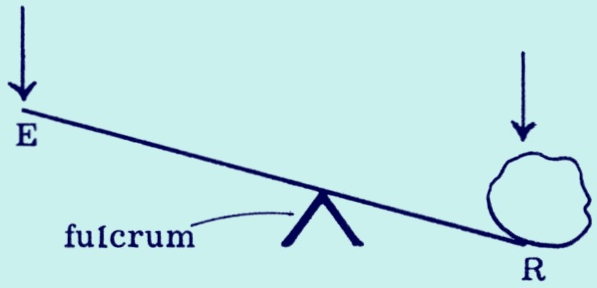

Fig. 2

You can demonstrate this principle by means of the 5-inch wooden stick and the dowel in your unit. Insert the stick one-half inch under a heavy book. Measure one inch from the half-inch point and place the dowel, which serves as the fulcrum, under the stick at this point. Push down on the end of the stick and note what little effort is required to lift the book. Now try to raise the book by merely lifting the stick. Note the difference in effort required.

The length of the effort arm here is 3½ inches and the length of the resistance arm is one inch. Using the equation,

$$MA = \frac{E_a}{R_a},$$

$$MA = \frac{3.5}{1} = 3.5$$

The output force exerted on the book

is found to be 3½ times as great as the input force.

Thus in order to raise a 3½-pound book one inch, the lever will have to be pushed down 3½ inches with a force of one pound.

Experiment 2. Another form of the first class lever is the arm balance.

Completely across one of your 5-inch sticks, mark off ⅛-inch spaces. Screw in a screw eye at the 1½-inch mark. Take a 3-inch length of your string and tie it to the screw eye. This will be the fulcrum. Pass a 5-inch piece of string through the center of the large pulley (1⅜ by $^{11}⁄_{16}$ inch) and tie the ends together forming a loop. Do the same with the 1¼-inch pulley. These will serve as weights. Slip the larger weight over the short end of the lever, and the smaller over the longer end, holding the lever suspended from the string. Slide the weights toward the center until the lever is balanced and horizontal. When the lengths of the arms times the weights are equal, the lever will balance. The ratio of E_a to R_a is the mechanical advantage.

For example, if R_a is ⅜ inch and E_a, $^{1}⅜$ inch, MA is 4. What results do you get?

Show that scissors and pliers are first

class levers.

Experiment 3. Second class levers. In this type of lever, the fulcrum is at one end of the lever and the resisting force is between the fulcrum and the acting force or effort (Fig. 3a).

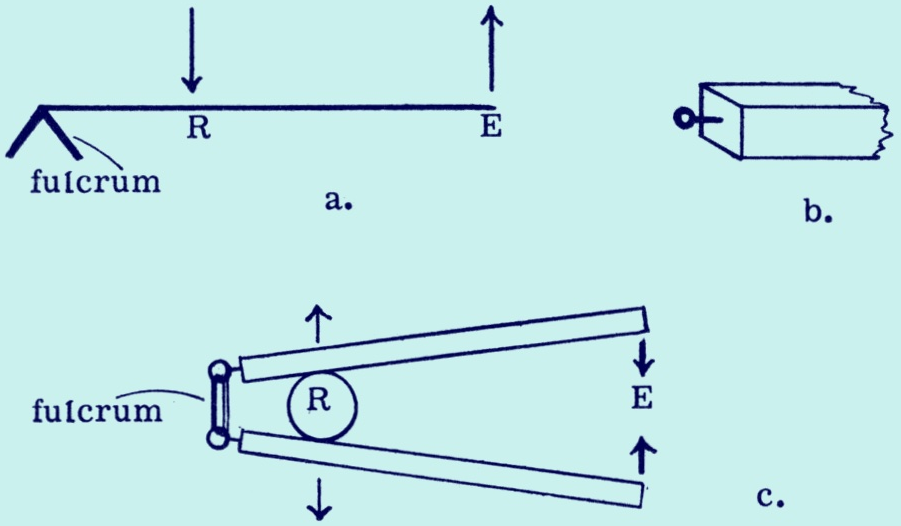

Fig. 3

Remove the screw eye used in the previous experiment and insert it into the center of the sawed-off end of the stick (Fig. 3b). Place a screw eye in the end of the second stick also. Place the two sticks side by side flat against each other with both the screw eyes at one end. Tie the screw eyes together, not too tightly, with a piece of your twine, or a rubber band if you have one handy. You now have a nutcracker. Place the large pulley or other small object between the two sticks to represent a nut and squeeze the

free ends together as if to crack the nut (Fig. 3c).

The tied ends form the fulcrum, the resisting force R is the nut and the effort force E is at the ends.

Can you explain why a wheelbarrow and paper cutter are also levers of the second class?

In second class levers, the mechanical advantage is greater than one, while in the first class lever, it can be either greater or less than one.

In the first class lever, the input force and the output force are in opposite directions, but in the second class lever, they are both in the same direction. Can you demonstrate this?

Experiment 4. Third class levers. Here the mechanical advantage is less than one.

The fulcrum in the third class lever as in the second class lever is at one end, but the acting force is between the fulcrum and the resisting force, and the resistance arm is longer than the effort arm (Fig. 4a).

A good example of this is given in the human body. The forearm acts as a third class lever with the fulcrum at the elbow. If a weight is held in the hand, the effort force is exerted by the muscles (biceps)

that pull the arm up (Fig. 4b).

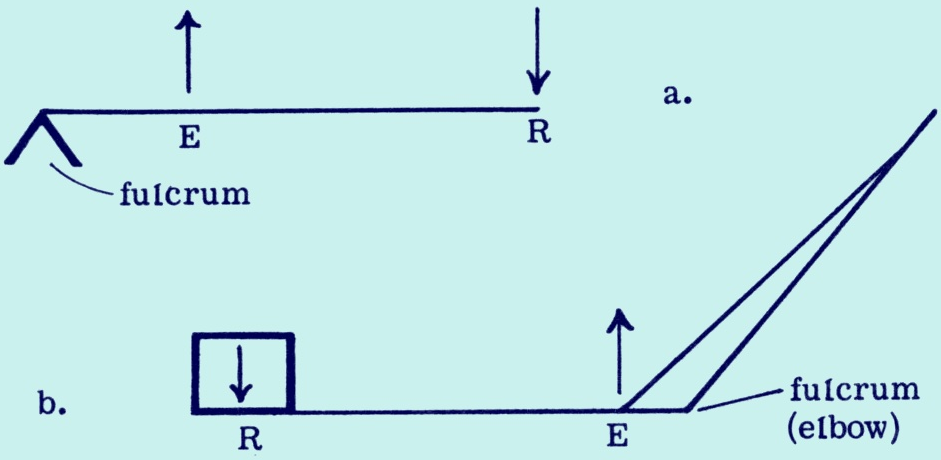

Fig. 4

Take one of your wooden sticks with the screw eye inserted at one end. Tie a 4- or 5-inch string securely to the stick about 1 inch from the end with the screw eye. Hold the screw eye lightly between the forefinger and thumb and pull up on the string with your other hand. This upward movement demonstrates what happens when your forearm is raised.

Using the measurements above, if the distance from the fulcrum (or elbow) to a load at the opposite end is five inches, then R_a is five inches long. The distance from the fulcrum to the string, or E_a, is one inch. The mechanical advantage, MA, therefore, would then be ⅕, or less than one. The effort force needed to lift the weight, thus is five times the resistance force of the load.

What common tools are third class

levers? Can you explain why a shovel and a broom are third class levers?

What classes of levers are represented by the oar of a rowboat in action?

INCLINED PLANE

Another familiar type of simple machine is the inclined plane. An inclined plane is a sloped flat surface like the side of a hill. The ancient Egyptians applied the inclined plane to move heavy stones when building pyramids and today, the inclined plane is used to move heavy objects such as pianos and trunks. The ramp used in some buildings instead of steps takes advantage of the principle of an inclined plane. Note how much easier it is to walk up a ramp than to climb stairs.

The mechanical advantage of an inclined plane is equal to the length of the plane divided by its vertical height, or

$$\text{MA} = \frac{\text{length of plane}}{\text{height of plane}} = \frac{\text{effort distance}}{\text{resistance distance}}$$

If a weight of 500 pounds is lifted 10 feet, along an inclined plane of 40 feet, then,

$$\text{MA} = \frac{40}{10} = 4$$

and

$$\text{horizontal force} = \frac{500 \text{ pounds}}{4} = 125 \text{ pounds}$$

Thus, in order to lift a 500 pound object 10 feet, the effort force required is 125 pounds.

Experiment 5. The screw is an inclined plane. Look at the threads of your screw eye. Note how they wind around. The greater the number of threads to the inch in a screw, the less the effort required to turn the screw and greater the mechanical advantage.

Note how much more effort is required to climb up a steep bank than a gently sloped one.

To show that a screw is an inclined plane, take plain white paper and cut out a right triangle 2½ inches high with a base of 4 inches. The hypotenuse of the triangle, the side opposite the right angle, is an inclined plane. Draw a heavy line along this edge with a colored pencil. Place the shorter edge of the paper triangle up against the dowel. Wind it around the dowel keeping the base even and note how the hypotenuse forms the "threads" of the screw.

When a screw is turned one complete revolution, it moves the distance between two threads, or the pitch. Demonstrate this.

The jackscrew is a combination of the lever and the inclined plane. To lift a heavy object such as a car or house the short distance of the pitch of the jackscrew, the arm of the jackscrew, or lever, must be turned a full circle.

The mechanical advantage MA of a jackscrew is the circumference of the circle made by the lever arm divided by the pitch of the screw, or the radius of the lever arm circle (r) times 2 π, divided by the pitch, since the circumference of a circle is $2\pi r$. $\pi = 3.1416$.

$$MA = \frac{\text{circumference}}{\text{pitch}} = \frac{2\pi r}{\text{pitch}}$$

If the radius of the lever arm of a jackscrew is 9 inches and the pitch 1 inch, what is the MA of the jackscrew?

The wedge is another adaptation of the inclined plane.

WHEEL AND AXLE

The wheel and axle may be considered as a lever system with the fulcrum at the center of rotation and the two radii of the lever arms in continuous rotation.

The radius r of the axle is the resisting arm (R_a) of the force and the radius R of the wheel, the effort arm (E_a) of

applied force. The MA of the wheel and axle is the large radius of the wheel divided by the radius of the axle, or R/r

$$\text{or MA} = \frac{E_a}{R_a}$$

The principle of the wheel and axle can be demonstrated in the windlass used to lift loads or to obtain water from an old-fashioned water well.

Experiment 6. To construct such a system, wind one end of one of your 5½-inch pieces of wire around the end of the wooden dowel and shape it into a crank (Fig. 5). Tightly secure a piece of string six inches long to the dowel and attach any small load to the free end of the string. At about the center of each of the wooden sticks, screw in two screw eyes just a little over ¼ inch apart. Place the two pieces of wood about two inches apart and place the dowel between the screw eyes so that the weight hangs between the two pieces of wood and the crank is on the outside (Fig. 5). Turn the crank and you wind up the twine. The MA of this system is the ratio of the length of the crank to the radius of the dowel. What is the MA of the windlass you have constructed?

$$MA = \frac{R}{r}$$

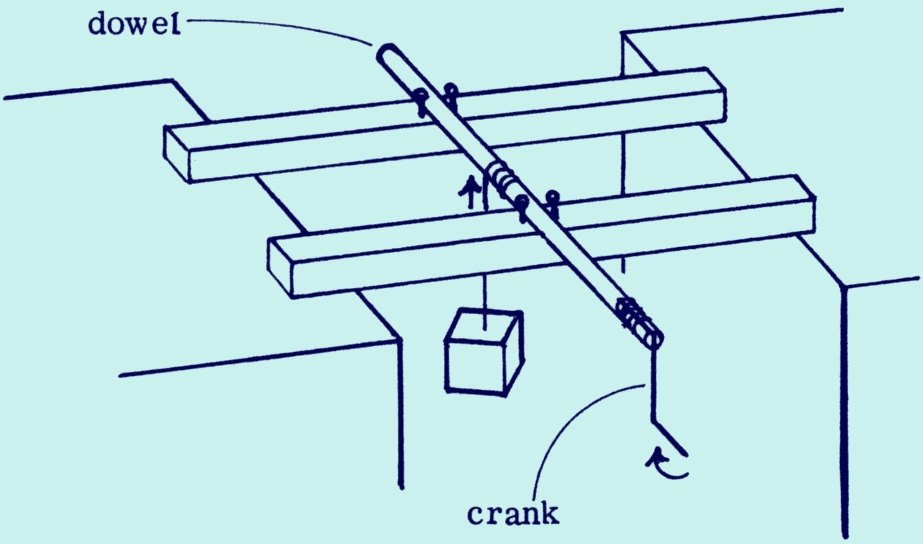

Fig. 5

PULLEYS

A pulley is a wheel with a grooved rim. The grooved rim is known as the sheave of the pulley. Look at your specimens and note their structure.

Pulleys are used primarily to make it easier to lift loads and/or to distribute the weight of a heavy object by increasing the mechanical advantage. A pulley system usually consists of a fixed pulley and a movable pulley.

You are no doubt familiar with many pulley systems, such as the crane and the elevator.

In your unit you will find four pulleys that are similar except for diameters.

Experiment 7. Screw a screw eye into the side of one of the square sticks. Pass the other 5½-inch wire strip through the central hole of your 1¼-inch diameter pulley and shape the wire into a form similar to a coat hanger (Fig. 6a) and hook it into the screw eye. Be sure the pulley will rotate freely. You now have a fixed pulley (Fig. 6b).

Cut a 12-inch length from your string. Tie any small object, such as a clothes pin or the heavy pulley in your unit, to one end, as a weight. Pass the free end over the pulley. Pull down on the string to raise the weight.

This is an example of a rope over a single fixed pulley. The mechanical advantage here is one. The effort needed to pull the weight up is equal to the weight. There is no advantage in work, but the direction of the force is changed which is often convenient in certain operations.

Experiment 8. Next unhook the pulley and tie the string securely to the screw eye. Attach the weight to the wire inserted in the pulley. Pass the string around the single pulley so that you have a movable pulley with a load attached (Fig. 6c).

Since one end of the string is secured to the screw eye, the free end of the

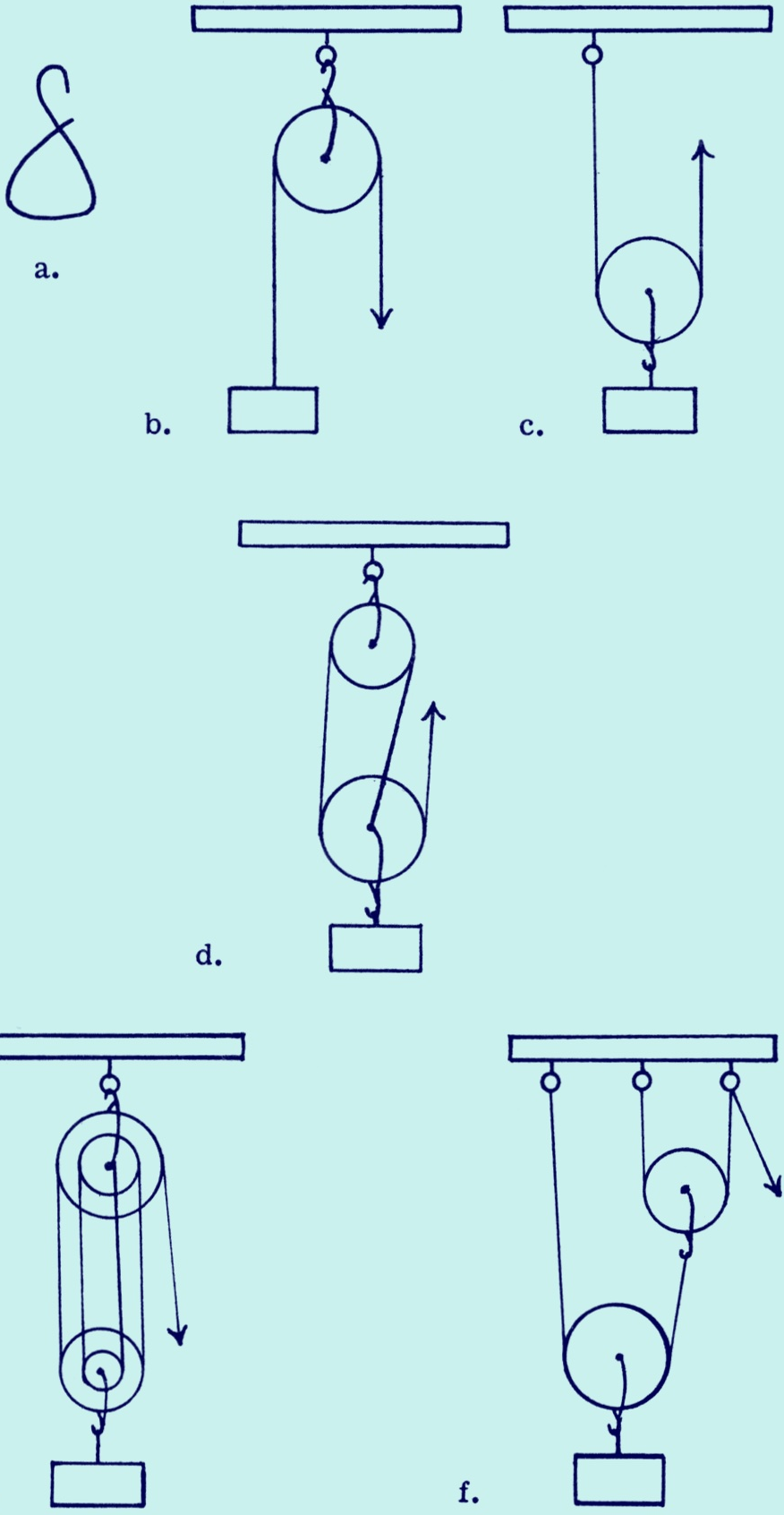

Fig. 6

twine supports only one-half the weight, the ideal mechanical advantage here is two.

Experiment 9. Make another loop with the wire used for the crank and insert the next smaller size pulley into it. Hang the pulley from the screw eye. Attach one end of the string to the wire hanger of the larger pulley with the weight still attached. Pass the free end of the string over the smaller pulley and around the lower edge of the larger pulley and up. The pulley system now has a mechanical advantage of three, since three ropes are supporting the weight and the force required to lift the weight is ⅓ (Fig. 6d).

Experiment 10. Make up a system of four pulleys by inserting two pulleys into each wire hanger. Hook one set of two pulleys to the screw eye and then tie a length of string to the wire supporting these two pulleys.

The other set of two will form the lower pulleys which will hang free with the weight attached.

Pull the string around the smaller of the bottom two pulleys, up and around the attached pulley on the same side and down again around the larger free pulley, then up and around the fourth pulley (Fig. 6e).

The mechanical advantage is 4 and the force required to lift the weight is ¼ the weight. If the load weighed 100 pounds, only 25 pounds of force would be required to lift the weight.

How would you increase the mechanical advantage to five?

Experiment 11. Screw 3 screw eyes about ¾ of an inch apart on the square stick. Attach a weight to the 1¼-inch pulley as before and suspend the pulley and weight on a string tied to the first screw eye. Fasten the free end of this string to the ¾-inch pulley to which another wire hanger has been attached. Tie a string to the second screw eye and pass it around the ¾-inch pulley. Pass the string through the third screw eye. What is the mechanical advantage of this system? Can you explain why MA = 4 (Fig 6f)? Put in another screw eye and suspend a third pulley. Connect it in the same way. What is the MA?

Experiment 12. The principle of the Chinese capstan, used to lift heavy weights, can be demonstrated with the materials in your unit.

Insert the dowel into the center hole of the heavy pulley so that it protrudes ½ inch from the opposite side. The dowel should fit tightly so that when the pulley

is turned, the dowel will turn with it. If the dowel is slightly large for the hole, it can be easily sanded down to fit. If a little loose, tighten with a small piece of tissue or other thin paper. Convert one of your wire hooks into a crank again and attach it tightly to the longer end of the dowel.

Use the square wooden pieces with the screw eyes in place as for the windlass constructed for Experiment 6, and prop them across two upright books to form a well about eight inches or more deep (Fig. 7).

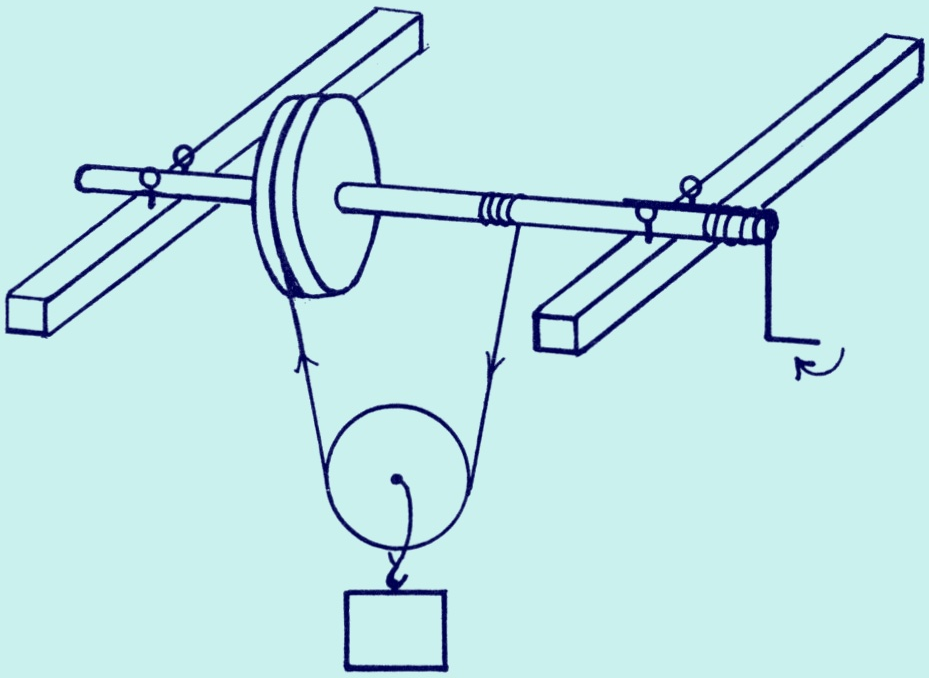

Fig. 7

Tie one end of a 2-foot long piece of string onto the pulley so that it will wind when the crank is turned clockwise. On

the dowel, tie the other end of the string securely and then wind it around in the opposite direction several times. On the loop of string between the two place a pulley with a weight attached. Now turn the crank. When the crank is turned clockwise, the string winds around the larger pulley and unwinds from the dowel and vice versa. The weight of the load is divided between the two parts of the string. The MA is 2. The force on the axle is relieved, hence heavier loads may be lifted.

The capstan is a form of differential pulley.

The differential pulley consists of a fixed upper pulley with two sheaves of different diameters fastened securely together and a single movable pulley with a weight attached. An endless rope or chain passes over one of the grooves in the fixed pulley, down and around the lower movable pulley with the weight, and then up and over the second groove in the upper pulley. As the rope is pulled, one of the grooves in the fixed pulley winds the rope while the other unwinds it.

Experiment 13. The principle of the differential pulley can be demonstrated by using the dowel and pulley again. Remove the crank for this experiment.

Pass the string over the pulleys as shown

in Figure 8 and then tie the ends together.

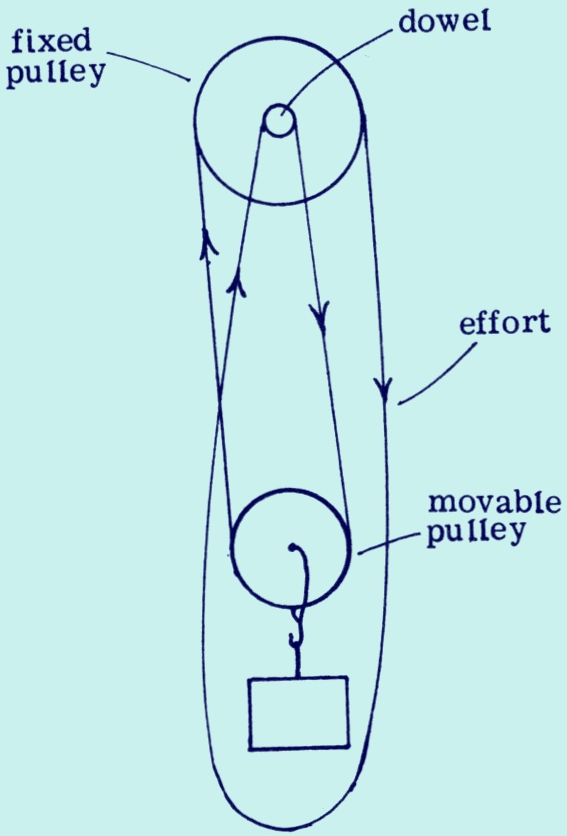

Fig. 8

Place the dowel on the square sticks between the screw eyes as before, allowing the string to hang between the books. Now gently pull down the freely hanging loop from one side, at "effort" in Fig. 8. Is the load raised or lowered? Pull the string from the opposite side. What effect does this have? What happens to the pulley with the load?

The MA of a differential pulley is 2 times the radius of the larger of the two fixed pulleys divided by the difference in the radii of the two.

The smaller the difference in the radii of the two parts of the fixed pulleys, the greater the MA.

$$MA = \frac{2R}{R - r}$$

The differential pulley is very useful where heavy loads need lifting.

In an actual differential pulley, the grooves in the upper pulley have notches to hold the chain and prevent it from slipping with the weight.

GEARS

Gears are devices sometimes used to change the speed of rotation of a mechanism, change direction of motion and especially to produce a non-slipping drive.

The amount that the rotation is multiplied in a gear system is the mechanical advantage.

Experiment 14. To make your gears, cut out the two disks and slit them along the short lines drawn from the outer edge to the inner circle.

Bend each of the cut sections alternately, one up and one down, along the edge of the circle and at right angles to it. Do this with both the cut-outs. Set the two disks thus formed aside.

Cut strips from the corrugated paper,

one about 10 inches long, 27 corrugations, and the other about 8 inches long, 23 corrugations. Separate the corrugated section from the backing from three corrugations at one end of each of the strips and fit them over three corrugations at the other end of the strips and paste them together so that you will have two wheels, one with 24 or 25 teeth to fit around the larger disk, and the other with 19 or 20 teeth for the smaller disk, depending on how they fit. Apply paste to the inside surface of the wheels and slip the disks you have prepared inside the wheels. Press the cut perpendicular sections against the inside of the wheels firmly. Be sure to center the disks and then allow the glue to dry completely. You now have two gear wheels.

After the glue has dried insert a thumbtack through the center of each gear wheel (dot at center of disk), and then mount the wheels on the ends of the square sticks; one wheel on each stick. Push the thumbtacks in securely but allow enough freedom for the wheels to rotate easily.

Intermesh the gear teeth and slide one gear against the other. Note the direction in which they rotate. They either rotate toward each other or away from each other.

The ratio of the number of gear teeth is the mechanical advantage.

Experiment 15. Mark one of the teeth in each of the gears with colored pencil or ink marker. Place these gear teeth next to each other and rotate them carefully. How many revolutions does the small gear make to the larger?

$$\text{MA} = \frac{\text{number of gear teeth of larger wheel}}{\text{number of gear teeth of smaller wheel}}$$

$$= \frac{24}{20}$$

Take the six-inch strip of corrugated paper left over and run the smaller gear attached to the stick over the corrugations. You now have a model of a rack and pinion.

Experiment 16. If a third gear were placed between the two gears how would their rotations be affected?

To demonstrate what happens, cut a three-inch piece from the remaining corrugated strip and roll it into a small wheel with about 8 teeth. Place this between the two other gears and rotate them. Are your results what you expected them to be?

Experiment 17. One wheel may drive another by means of a belt. In such cases, the wheel with the smaller radius makes

more revolutions per minute (rpm) than the larger wheel. The ratio of the increase in rpm is inversely proportional to the ratio of the radii of the wheels. This means that the rpm of the smaller wheel increases as its radius decreases in relation to the larger wheel.

Show this relationship by doing the following experiments.

Secure the 1¼-inch pulley and the 1-inch pulley about three inches apart in one of the square wooden sticks with your thumbtacks. With a piece of string or rubber band, make a belt around the two. Draw a radius on each of the pulleys to serve as a marker. Now turn one pulley and note how many times the other rotates with one rotation of the first. Replace the 1-inch pulley with the ¾-inch one and do the same. Repeat the experiment with the ½-inch pulley.

On the second wooden stick secure the 1-inch and ¾-inch pulleys three inches apart with thumbtacks, leaving the 1¼-inch and the ½-inch pulleys on the first stick. Place the two sticks three inches apart and loop a belt around all four pulleys. Secure the sticks so they will not move. Turn one of the pulleys. Keep the belt taut so the wheels will turn evenly. Do you find the same relationship

in speed of rotation as you did above?

Repeat the experiment with the various sized pulleys in different combinations and note that the speed of rotation depends on the radii of the wheels.

Experiment 18. Secure two pulleys three inches apart on the stick as before. Place a belt around the two twisting it once so that the strings cross. In what direction does the second wheel now turn when the first is rotated?

Belts have many applications in machines. The larger the one wheel is in proportion to the second, the greater the speed obtained in the smaller wheel.

The fan belt in a car is a typical example. Note the modification shown by the chain and sprocket drive on a bicycle.

Many other experiments can be devised to show the principles of simple machines with the equipment in this unit. See how many you can think of and demonstrate.

Appreciation is expressed to Mr. Douglas R. Tate, U. S. National Bureau of Standards, for reviewing this booklet.

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THINGS of science

SIMPLE MACHINES

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